



**CALIFORNIA  
ENERGY  
COMMISSION**

## **New Wind Energy Resource Maps of California**

# **CONSULTANT REPORT**

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## Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million to conduct the most promising public interest energy research by partnering with Research Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for the Wind Resource Mapping Project, Contract number 500-01-009, conducted by TrueWind Solutions. The report is entitled New Wind Energy Resource Maps of California. This project contributes to the Renewable Energy Program.

For more information on the PIER Program, please visit the Commission's Web site at <http://www.energy.ca.gov/research/index.html>, or contact the Commission's Publications Unit at 916-654-5200.

## **Executive Summary**

This report describes a wind-mapping project conducted by TrueWind Solutions for the California Energy Commission. The purpose of this contract is to develop more accurate and reliable wind resource maps for California using state-of-the-art numerical modeling techniques and site validation data. This effort not only updates the existing annual wind resource map for California produced in the late 1970s, but includes several enhancements, including the incorporation of new meteorological, geographical and terrain data that have been collected but were unavailable when the original map was produced. Validation of map results also has been performed in conjunction with the modeling effort. These new maps will help to better define wind corridors as well as identify new potential sites for wind energy integration.

### **Objectives**

The specific technical objectives were as follows:

- Access state-of-the-art numerical modeling techniques to predict wind speed and power at various heights and to refine those predictions with validation data gathered from various meteorological towers throughout the state.
- Create updated, high-resolution wind resource maps for California, including maps of wind speed and wind power at varying heights.
- Create maps depicting the seasonal variability of the wind resource.
- Create computer files of wind resource data that are ready for immediate integration into State cartography system (GIS format).

### **Approach**

The MesoMap system consists of an integrated set of atmospheric simulation models, databases, and computers and storage systems. At the core of MesoMap is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model that simulates the complete physics of the atmosphere. MASS is coupled to a simpler wind flow model, WindMap, which is used to refine the spatial resolution of MASS to account for the local effects of terrain and surface roughness. MASS simulates weather conditions over the region for 366 historical days randomly selected from a 15-year period. When the runs are finished, the results are input into WindMap for the final mapping stage. In this project, the MASS model was run on a grid spacing of 2 km, and WindMap on a grid spacing of 200 m.

The preliminary wind maps produced by MesoMap were thoroughly validated by TrueWind Solutions in collaboration with NREL and independent consultants. The validation process used data for 262 stations from a wide variety of sources, including airports, ocean buoys, and towers instrumented specifically for wind resource assessment.

The validation concluded that the initial wind speed estimates at 50 m height, before any adjustments, were accurate to within a standard error of 0.4-0.6 m/s, or 6% to 8%. Qualitatively, the preliminary maps presented an accurate overall picture of the wind resource, but tended to underestimate winds in certain well-known wind corridors and to overestimate winds on mountaintops. We believe that the most important source of error is the finite grid scale of the

MASS simulations, a consequence of the size of the state and limitations of budget and schedule, which resulted in an inability to fully resolve passes through mountains or the blocking of low-level winds by mountain ranges.

Following the validation, the wind maps were adjusted to improve the agreement with the data, and the revised maps were reviewed once more. We avoided adjusting the maps for specific points, but rather attempted to correct for clear patterns of error occurring over sizable regions. The speed adjustment ranged from a decrease of up to 15% to an increase of up to 25%. Most adjustments were around 5-10% in either direction.

## **Outcomes**

Using our MesoMap system, which was developed over four years ago, we have produced new maps of California's mean wind speed and power for a range of heights above ground on a 200 m grid. We have also produced data files of the predicted frequency, mean speed, and energy by direction, as well as the seasonal characteristics of the resource. (The data files are provided separately on a CD-ROM.) The validation process provided a mechanism for objectively comparing the wind maps against data from a wide variety of sources, for estimating the map errors, and for independent review of the maps by leading wind energy consultants and government researchers. The final, published wind maps have been adjusted to reflect the validation findings and, consequently, represents the best current estimate of California's wind resources, at a very high resolution.

## **Conclusions, Recommendations, and Benefits to California**

The preliminary map estimates correlated well with data obtained for 266 towers and extrapolated to a height of 50 m, indicating that the method overall is sound.

Aside from confirming the existence of several well-known wind resource areas, the maps point to a number of other promising sites, some already known to wind energy experts and others perhaps previously unsuspected.

The report concludes with some recommendations for further research. The main recommendations are: (1) High-resolution mapping of promising areas to better resolve mountain blocking and channeling effects and consequently to improve the accuracy of the wind resource estimates; (2) research to improve methods of simulating the stable nighttime boundary layer and its effects on wind speeds at the hub height of turbines; (3) the development of an improved data base of land cover and surface roughness throughout the state; and (4) a new program of measurement of winds at or near the hub height of large turbines using tall towers, sodar, and other tools.

The project's potential benefits to California include the following:

- Improving energy cost/value of California's electricity by accelerating the initial stages of wind project development with reliable wind maps that substantially reduce risk and siting barriers for new developers
- Improving electricity reliability/quality/sufficiency of California's electrical system by providing the most current and reliable information on wind resource data for the State.
- Providing data for identifying new potential sites for wind energy integration

- Providing high-resolution wind data useful for forecasting and optimizing wind resource management.
- Strengthening the California economy by encouraging development of new wind sites and job opportunities.
- Providing greater choices for California consumers by supporting the expansion of clean energy resources and by providing data to make the resources more manageable.
- Improving the environment, public health and safety by providing the most reliable and updated data for basing decisions and integrating with existing infrastructure (transmission) and planning strategies.

## **Abstract**

The MesoMap system has been used to produce new wind energy resource maps and databases for the State of California on a 200 m grid. The wind resource maps confirm the locations of several major wind resource areas and also point to the existence of new areas that may not be widely known. An objective validation process, carried out using data from over 260 sites throughout the state and advice from independent consultants, concluded that the preliminary wind resource estimates were accurate to a standard error of 0.4-0.6 m/s (6-8%). Adjustments to the maps were subsequently made to improve the match to the data. The adjustments included increases in the predicted resource within some known wind resource areas, and reductions along some mountaintops and in some coastal areas. The finite grid scale of the model is suspected of being the main cause of the observed errors. The project has resulted in the most accurate current assessment of wind resources in California at a scale suitable for identifying promising sites for wind energy projects. Several topics for further research are suggested to help improve the accuracy of the maps in promising resource areas.

## **1.0 Introduction**

### **1.1. Background**

Just as the growth of the petroleum industry in the early 20th century depended on the discovery of new oil fields by prospectors and wildcatters, the growth of the modern wind energy industry – and its ability to meet growing energy needs – depends on the discovery of new sites having a useful wind resource. California, in fact, has extensive experience with wind resource assessment, having conducted some of the first such studies in the world in the late 1970s and early 1980s, which resulted in large wind installations in Altamont Pass, Tehachapi Pass, and several other areas. These studies produced a picture of California's wind resources, that served the state remarkably well through the 1990s.

Great strides in computer technology and the development of new wind resource mapping tools and methods have now made it possible to update and refine California's wind resource maps. These new techniques have the potential to increase the amount and accuracy of information placed in the hands of the public, enabling anyone from major developers to individual enthusiasts to identify prospective sites for wind energy systems. Of course, mapping is just the first stage of the siting process. Promising sites identified in maps must be confirmed through field assessments and monitoring, and other hurdles, such as permitting and environmental impact assessments, must be overcome. Nevertheless, the availability of more detailed wind resource information should accelerate the siting process and enable more people and companies to participate in it.

The purpose of this contract was to develop more accurate and reliable wind resource maps for California using state-of-the-art numerical modeling techniques and site validation data. This effort not only updates the existing annual wind resource map for California produced in the late 1970s, but includes several enhancements including the incorporation of new meteorological, geographical, and terrain data that have been collected but were unavailable when the original map was produced. The validation of map results has been performed in conjunction with the modeling effort. These new maps will help to better define wind corridors as well as identify new potential sites for wind energy integration

### **1.2. Objectives**

The objective of this project was to create a new wind resource map and database of California using advanced computer tools at the highest possible spatial resolution. The wind resource data were to be produced in format that could be imported and used in a Geographical Information System (GIS). The project had the additional objective, in keeping with the PIER programs mandate, to support scientific studies, to objectively estimate the accuracy of the maps, and to identify weaknesses in the method and data that should be addressed through research. The specific technical objectives were as follows:

- Access state-of-the-art numerical modeling techniques to predict wind speed and power at various heights and to refine those predictions with validation data gathered from various meteorological towers throughout the state.
- Create updated, high-resolution wind resource maps for California, including maps of wind speed and wind power at varying heights.

- Create maps depicting the seasonal variability of the wind resource.
- Create computer files of wind resource data that are ready for immediate integration into State cartography system (GIS format).

### **1.3. Report Organization**

In Section 2.0, we describe the MesoMap system and mapping process in detail: how MesoMap was applied in this project, the process by which the initial maps were validated, and the validation results and map adjustments. In Section 3.0 we present the outcomes of our approach to the project. In Section 4.0, we close with some conclusions, recommendations for further research, and a review of the project's benefits to California.

Guidelines for the use of the maps are contained in Appendix I. Appendix II presents information on how to use the Data CD associated with this report. The final wind maps and data file are contained in Appendix III.

## **2.0 Approach**

### **2.1. Description of the MesoMap System**

The MesoMap system has three main components: models, databases, and computer systems. These components are described below.

#### **2.1.1. Models**

At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model that has been developed over the past 20 years by TrueWind partner MESO, Inc., both as a research tool and to provide commercial weather forecasting services. MASS simulates the fundamental physics of the atmosphere including conservation of mass, momentum, and energy, as well as the moisture phases, and it contains a turbulent kinetic energy module that accounts for the effects of viscosity and thermal stability on wind shear. As a dynamic model, MASS simulates the evolution of atmospheric conditions in time steps as short as a few seconds. This creates great computational demands, especially when running at high resolution. Hence, MASS is usually coupled with a simpler but much faster program, WindMap, a mass-conserving wind flow model. Depending on the size and complexity of the region and requirements of the client, WindMap is used to improve the spatial resolution of the MASS simulations to account for the local effects of terrain and surface roughness variations.

#### **2.1.2. Data Sources**

The MASS model uses a variety of online, global, geophysical and meteorological databases. The main meteorological inputs are reanalysis data, rawinsonde data, and land surface measurements. The reanalysis database – the most important – is a gridded historical weather data set produced by the US National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). The data provide a snapshot of atmospheric conditions around the world at all levels of the atmosphere in intervals of six hours. Along with the rawinsonde and surface data, the reanalysis data establish the initial conditions as well as updated lateral boundary conditions for the MASS runs. The MASS model

itself determines the evolution of atmospheric conditions within the region based on the interactions among different elements in the atmosphere and between the atmosphere and the surface. Because the reanalysis data are on a relatively coarse, 200 km grid, MASS is run in several nested grids of successively finer mesh size, each taking as input the output of the previous nest, until the desired grid scale is reached. This is to avoid generating noise at the boundaries that can result from large jumps in grid cell size. The outermost grid typically extends several thousand kilometers.

The main geophysical inputs are elevation, land cover, vegetation greenness (normalized differential vegetation index, or NDVI), soil moisture, and sea-surface temperatures. The global elevation data normally used by MesoMap were produced by the US Geological Survey in a gridded digital elevation model, or DEM, format from a variety of data sources. (The US Defense Department's high-resolution Digital Terrain Elevation Data set is the principal source for the global 1 km elevation. Gaps in the DTED data set were filled mainly by an analysis of 1:1,000,000 scale elevation contours in the Digital Chart of the World, now called VMAP). The US Geological Survey, the University of Nebraska, and the European Commission's Joint Research Centre (JRC) produced the global land cover data in a cooperative project. The land cover classifications are derived from the interpretation of Advanced Very High Resolution Radiometer (AVHRR) data – the same data used to calculate the NDVI. Both land cover and NDVI data are translated by the model into biophysical parameters such as surface roughness, albedo, and emissivity. The nominal spatial resolution of all of these data sets is 1 km. Thus, the standard output of the MesoMap system is a 1 km gridded wind map. However, much higher resolution maps can be produced where the necessary topographical and land cover data are available.

### **2.1.3. Computer and Storage Systems**

The MesoMap system requires a very powerful set of computers and storage systems to produce wind resource maps at a sufficiently high spatial resolution in a reasonable amount of time. To meet this need TrueWind Solutions has created a distributed processing network consisting of 94 individual Pentium II processors and 3 terabytes of hard disk storage. Since the days simulated by a single processor are entirely independent of other days, a project can be run on this system up to 94 times faster than would be possible with any single processor. To put it another way, a typical MesoMap project that would have taken two years to run on a single processor can now be completed in just one week.

### **2.1.4. The Mapping Process**

The MesoMap system creates a wind resource map in several steps. First, the MASS model simulates weather conditions over 366 days selected from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample; only the year is truly random. Each simulation generates wind and other weather variables (including temperature, pressure, moisture, turbulent kinetic energy, and heat flux) throughout the model domain, and the information is stored at hourly intervals. When the runs are finished, the results are compiled into summary data files, which are then input into the WindMap program for the final mapping stage. The two main products are usually (1) color-coded maps of mean wind speed and power density at various heights above

ground and (2) data files containing wind frequency distribution parameters. The maps and data may then be compared with land and ocean surface wind measurements, and if significant discrepancies are observed, adjustments to the wind maps can be made.

#### **2.1.5. Factors Affecting Accuracy**

In our experience, the most important sources of error in the wind resource estimates produced by MesoMap are the following:

- Finite grid scale of the simulations
- Errors in the topographical and land cover data bases
- Errors in assumed surface properties such as roughness

The finite grid scale of the simulations results in a smoothing of terrain features such as mountains and valleys. For example, a mountain ridge that is 2000 m above sea level may appear to the model to be only 1600 m high. Where the flow is forced over the terrain, this smoothing can result in an underestimation of the mean wind speed or power at the ridge top. Where the flow is blocked by the mountains, on the other hand, the smoothing can result in an overestimation of the resource, as the model understates the blocking effect. The problem of finite grid scale can be solved by increasing the spatial resolution of the simulations, but at a cost of far more computer processing.

Errors in the topographical and land cover data can create additional problems in the simulations. While elevation data are usually reliable, errors in the size and location of major terrain features nonetheless occur from time to time. Errors in the land cover data occur more often, usually because of misclassification of aerial or satellite imagery. It has been estimated that the global 1 km land cover database used in the MASS simulations is about 70% accurate. Where possible, more accurate and higher resolution land cover databases are used in the WindMap stage of the mapping process to correct such errors. In the United States, a 30 m gridded Landsat-derived land cover database is used; a similar 250 m database, called CORINE, is available for Western Europe.

Even if the land cover types are correctly identified, there is uncertainty in the surface properties that should be assigned to each type, and especially the vegetation height and roughness. The forest category, for example, encompasses many different varieties of trees with varying heights and density, leaf characteristics, and other features that affect surface roughness. Likewise, an area classed as residential may consist of a scattering of single-story dwellings or a large number of tall apartment buildings. Uncertainties like this can be resolved only by acquiring more information about the area through aerial photos or direct observation. However this is often not practical if (as in this project) the area being mapped is very large.

## **2.2. Implementation of MesoMap**

The standard MesoMap configuration was used in this project. MASS was run on the following nested grids:

- First (outer) grid level: 30 km
- Second (intermediate) grid level: 8 km
- Third (inner) grid level: 2 km

The 8 and 30 km grids covered the entire state. At the third grid level of 2 km, the region was broken up into five overlapping grids. The grid setup is shown in Map 1.

At the WindMap stage, high-resolution topographical and land cover data were used to obtain a final grid spacing of 200 m. The elevations were taken from the USGS 3-arc-second gridded topographical database of the United States, while the land cover classifications were from the USGS 30-meter gridded data set derived from Landsat imagery. Both data sets were resampled to 200 m; the elevations were resampled using bilinear interpolation, which smooths the terrain, whereas the land cover data were first filtered to identify the most frequent land cover class within a 200x200 m area, then resampled using a nearest-neighbor algorithm. The elevation map is shown in Map 2, the land cover map (reclassified into a few representative categories) in Map 3.

Table 1 lists the categories in the land cover database and the surface roughness values (in meters) initially assigned to them. The values chosen were judged to be typical for each land cover class. However, the actual roughness may vary a lot within a class (except water). The roughness may also vary by season because of changes in vegetation height and leafiness as well as snow cover.

**Table 1. Land Cover Classifications and Surface Roughness**

<b>Class</b>	<b>Description</b>	<b>Roughness (m)</b>
11	Open Water	0.001
12	Perennial Ice/Snow	0.001
21	Low Intensity Residential	0.3
22	High Intensity Residential	0.75
23	Commercial/Industrial/Trans	0.01
31	Bare Rock/Sand/Clay	0.01
32	Quarries/Strip Mines/Gravel Pits	0.1
33	Transitional	0.1
41	Deciduous Forest	0.9
42	Evergreen Forest	1.125
43	Mixed Forest	1.125
51	Shrub land	0.05
61	Orchards/Vineyards/Other	0.05
71	Grasslands/Herbaceous	0.01
81	Pasture/Hay	0.01
82	Row Crops	0.01
83	Small Grains	0.01
84	Fallow	0.01
85	Urban/Recreational Grasses	0.01
91	Woody Wetlands	0.66
92	Emergent Herbaceous Wetlands	0.1

From our experience mapping the Pacific Northwest, we were concerned that the roughness on high, forested mountaintops might be substantially lower than that shown in the table because trees tend to become shorter and more widely spaced with increasing elevation and exposure to the wind. We developed a tentative model of the variation of forest roughness with elevation,

similar to that used in our Northwest work, which depended on knowing where the tree line is. (The tree line is the elevation at which trees substantially disappear on high mountain slopes.)

However, the results, we concluded, were unsatisfactory, as the adjustment led to a substantial increase in the predicted wind resource on mountaintops, whereas it was concluded in the validation (as described in the next section) that the wind resource on mountaintops was generally overestimated. Consequently, the roughness adjustment was dropped in the final maps. It is clear that the question of tree height and density and their effect on the wind resource deserves further study.

### **2.3. Validation Procedure**

The validation was carried out in cooperation with NREL and consulting meteorologists using data from a large number and wide variety of sources. The participating meteorologists are listed below:

- Jack Kline, Consulting Meteorologist
- Ed McCarthy, WECTEC
- Ron Nierenberg, Consulting Meteorologist
- Richard L. Simon, Consulting Meteorologist

Each consultant provided data from his own sources, both proprietary and public, and NREL and TrueWind also contributed data. A standard spreadsheet table format was followed. The table included the station name, source of data, location, anemometer height, recorded mean speed, period of record, and comments about the site such as local land cover, if available. The locations of the data points are shown in Map 5.

TrueWind then analyzed the data in the following steps:

1. The spreadsheets from the various consultants were combined into one master spreadsheet. Duplicate stations were identified and eliminated. In a few cases it was necessary to reconcile conflicting estimates for the same station, either by picking what seemed to be the more credible of the estimates, or taking the average.
2. Station locations were then verified and adjusted, if necessary, by comparing the quoted elevations and station descriptions against the elevation and land cover maps. Where there was an obvious error in position, the station was either moved to the nearest point of correct elevation, or if a suitable location could not be found, it was eliminated. Position errors of up to 1 or 2 km arose quite often in the older and less well-documented data sets.
3. The observed mean speed and power were extrapolated to a common reference height of 50 m using the power law. Where possible, the measured shear exponent for the site was used. In most cases, however, the shear exponent had to be estimated; we generally followed the advice of the consultants concerning the shear at stations they were familiar with. The estimated shear exponent on exposed ridges and mountaintops ranged from 0.05 to 0.14; in open plains or broad valleys, from 0.14 to 0.16; and in deep, sheltered valleys, 0.16 to 0.20. Offshore, a value of 0.10 was used. Exceptions were made where it seemed likely the station was either unusually sheltered or the wind was

strongly influenced by channeling, compression over a ridge, or acceleration down a slope.

4. The error margin of each data point was then estimated as a function of two factors: the tower height and the number of years of measurement. The tower height enters the equation because of uncertainty in the wind shear. The measured shear exponents reported by the consultants varied with a standard deviation of about 0.07. Absent information about the sites, this could be interpreted as the standard error. However, we assumed that knowing something about the site and relying on the expertise of the consultants would reduce the variance by 50%, implying a standard error in the shear estimates of about 0.05. Where shear data were available, we assumed an error margin of 0.03 between the top anemometer and the map height; the same applied to all offshore data.

The period of measurement is significant because, even if a site is monitored for a year or more, the resulting mean speed may not be representative of the long term. A rule of thumb in the wind industry is that one year of measurement will result in a mean speed that is within 10% of the long term mean with 90% confidence. This can be translated into a standard error of 6% for one year of data. We assumed that interannual variations are normally distributed, so that the standard error goes down in inverse proportion to the number of years (or, if climatologically corrected, the number of years of the long-term reference).

The two uncertainties were then combined in a least-squares sum as follows:

$$(2) \quad e = \sqrt{\left(\left(\frac{50}{H}\right)^{0.05} - 1\right)^2 + \left(\frac{0.06}{\sqrt{N}}\right)^2}$$

where H is the height of the anemometer and N the number of years of measurement. For example, if the mean speed for a 10 m tower with a two-year record was 6.6 m/s, and the estimated shear was 0.14, then the estimated 50 m speed was 8.3 m/s with a standard error of 9.4%.

The true error margin may be substantially larger than that given by this equation for certain older and less well-documented data sets because of a lack of information about local site characteristics, equipment type, calibration, tower shadowing, and other factors. On the other hand, the error margin in the major wind resource areas is probably somewhat smaller.

5. The predicted wind speed and power at each station's position were then extracted from the raw (invalidated) maps. At first we did this using an automated GIS extraction routine, but we found that this resulted in frequent errors because of slight offsets in station locations and in the topographic and land cover data. Instead, we examined each point and extracted the most reasonable map value by hand. This necessitated a certain amount of judgment, but we think it is more reliable than using an automated process.
6. Next, the predicted and measured/extrapolated speed and power were compared, and the map bias (map speed or power minus measured/extrapolated speed or power) was

calculated for each point. Stations with especially large discrepancies (compared to the data error margin) were examined closely. In a few cases, the stations were eliminated. The decision to drop a station was made for one of the following reasons: (a) the observed mean speed or power appeared to be grossly inconsistent with other data for similar locations in the region; (b) the data recovery percentage was very low (below 50%); and (c) the location of the station was in serious doubt. Most of the stations that were excluded were short towers with unknown site characteristics and little other documentation. (Three buoys were eliminated because they appeared to duplicate other buoys in the station list but the reported mean speeds were 0.5-1 m/s higher. The three buoys, numbered 740124, 740134, and 740144, were all from the DATSAV database.)

7. The bias was then displayed in a scatter plot and on a bias map. A scatter plot allows the quick identification of outlying points and reveals the overall quality of the match between prediction and measurement. A bias map, on the other hand, is useful for revealing spatially correlated error patterns. If a cluster of stations have similar errors in sign and magnitude, it is more likely to reflect a real problem in the map than if the errors appear randomly distributed.

## 2.4. Quantitative Validation Results

Table 2 summarizes the results of the validation for wind speed. We did not compile comparable statistics for power because most of the stations did not have power data, and TrueWind did not analyze the power as closely as the speed. The table lists the number of non-duplicate stations received, the number retained after excluding questionable data, the root-mean-square (RMS) discrepancy, and the estimated model error.

**Table 2. Validation Summary**

<b>Non-Duplicated Stations</b>	<b>Stations Retained</b>	<b>RMS Discrepancy</b>	<b>Estimated Model Error</b>
279	262	0.76 m/s (11.1%)	0.51 m/s (7.4%)

The model error is calculated by subtracting (in a least-squares sense) the data error margin from the RMS discrepancy:

$$(3) \quad e_{MODEL} \approx \sqrt{e_{TOTAL}^2 - e_{DATA}^2}$$

This equation assumes that the model and data errors are both normally distributed and independent of one another. The model error is a more realistic estimate of the accuracy of the map as it accounts for the fact that some of the apparent discrepancy between the map and data is caused by errors in the data.

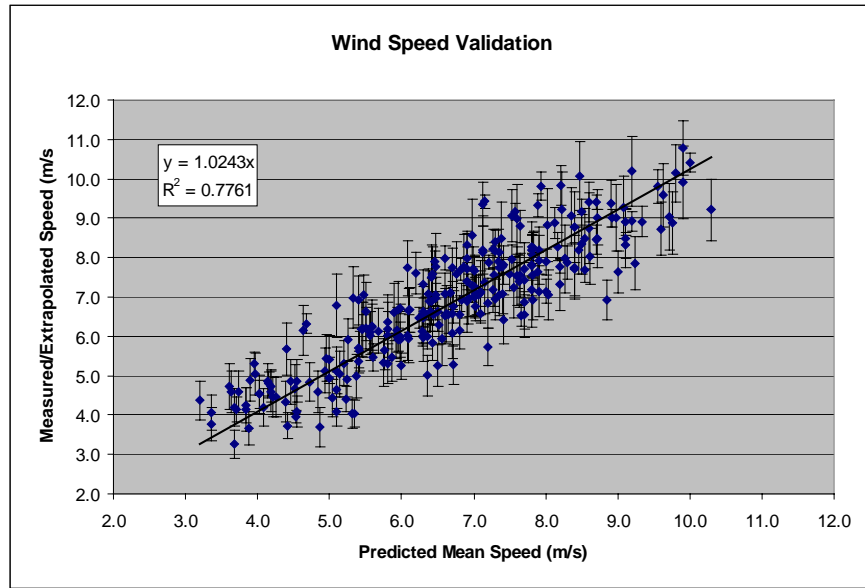


Figure 1. Scatter plot of predicted and measured/extrapolated mean wind speeds.

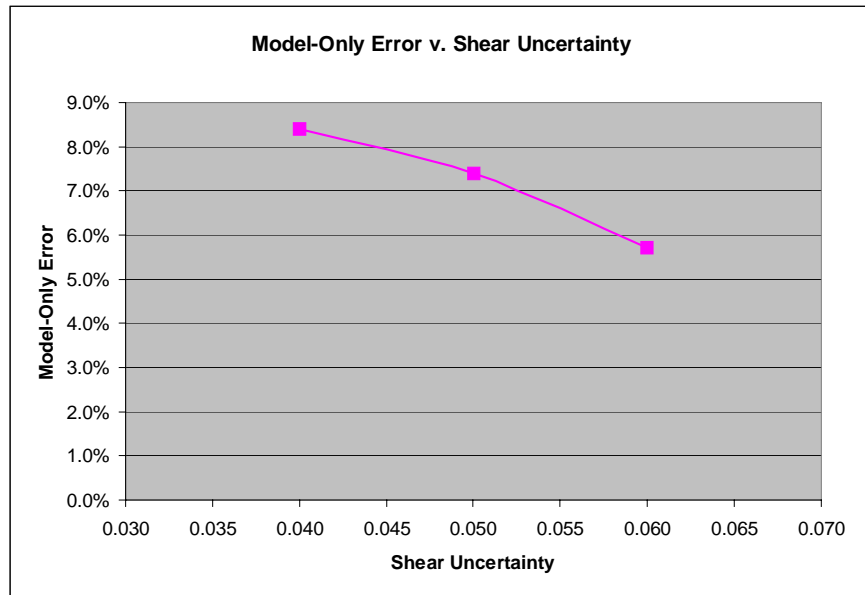


Figure 2. The relationship between the estimated model error and the uncertainty in wind shear.

The scatter plot in Figure 1 compares the predicted and measured-extrapolated mean wind speeds at 50 m height for 262 stations. Vertical error bars reflect uncertainty in the extrapolated data due to limited tower heights and periods of measurement. The error bars were calculated with Equation 3. The linear trend line, which is forced through the origin, indicates that the

predicted speed has little overall bias (about 2% on average) and explains 78% of the variance in the measured/extrapolated speeds; in addition, the bias does not vary significantly with speed.

Figure 2 shows that the estimate of the model error is quite sensitive to the assumed uncertainty in wind shear. The more uncertainty there is in the shear, the smaller the portion of the discrepancy between the map and data is attributable to the model. If the average uncertainty is actually 0.06 at most stations, rather than 0.05, the estimated model error drops to 5.7% (0.4 m/s); if the uncertainty is 0.04, the estimated model error increases to 8.4% (0.6 m/s). This sensitivity reflects the fact that most of the 262 towers in the data set were less than 20 m in height. The real uncertainty in shear probably varies widely, however. In the major wind resource areas it may be lower than average, whereas in remote locations where little other data has been collected, it may be higher.

## **2.5. Qualitative Observations and Sources of Error**

The main qualitative observations we received from the consultants can be summarized as follows:

- Essentially all known high-wind areas have been identified; however, the predicted mean winds at these sites have generally been under-predicted, with the exception of Tehachapi Pass.
- Low-wind areas generally have been predicted correctly by the map.
- Some high-wind areas have been predicted by the map, but there is no hard data to confirm their existence. The areas include most notably zones east of the Sierra Nevada in Kern County, from Inyokern to Haiwee.
- The mountaintop resource along the coast and in the northern interior may be somewhat overestimated, although the data are weak and the errors very location-dependent.
- Offshore winds are generally well represented, but there is a tendency for the model to overestimate the near-shore resource in the far north, and to underestimate it in the far south.

While there is no single cause of model errors, the most important single factor is probably the finite grid scale of the MASS simulations. This could explain, in large part, both the underestimation of the wind in the main wind corridors and the overestimation of the wind on some mountaintops.

For a finite-element model like MASS to be able to fully resolve mountain passes and wind corridors, it is necessary for the width of the pass to be spanned by at least six grid cells. (Although WindMap runs at a much higher resolution than MASS, its simplified equations do not permit the simulation of channeling through passes.) This criterion was not met in several instances; San Geronimo Pass, for example, is about 6-10 km wide whereas each MASS grid cell was 2 km. In addition, where there is significant acceleration down a slope because of warm valley temperatures, the zone of acceleration must be wide enough to meet the same criterion. This requirement was probably not met in Pacheco Pass. The effect of grid scale on the simulation of flow through mountain passes is illustrated in Figure 3 and Figure 4.

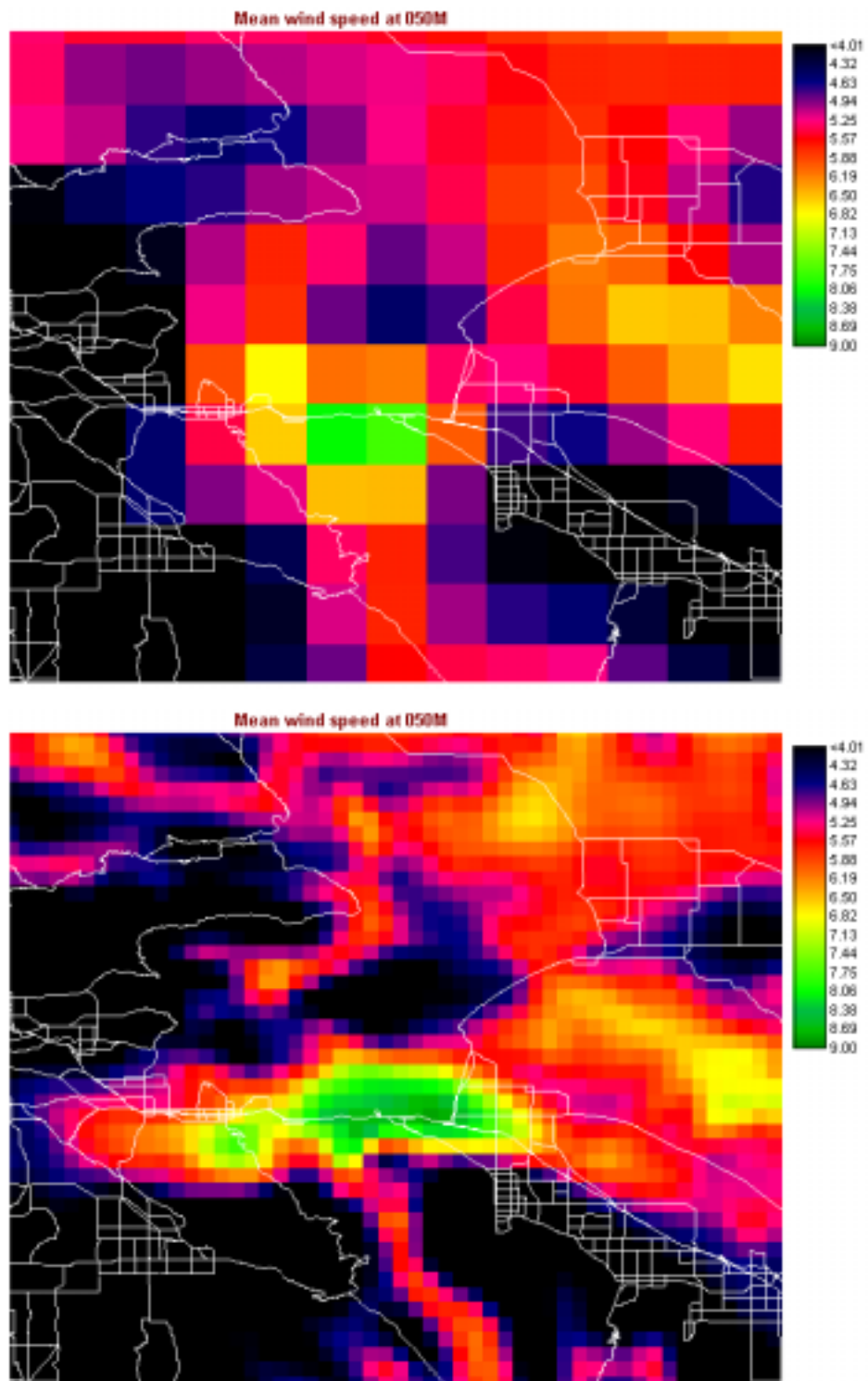
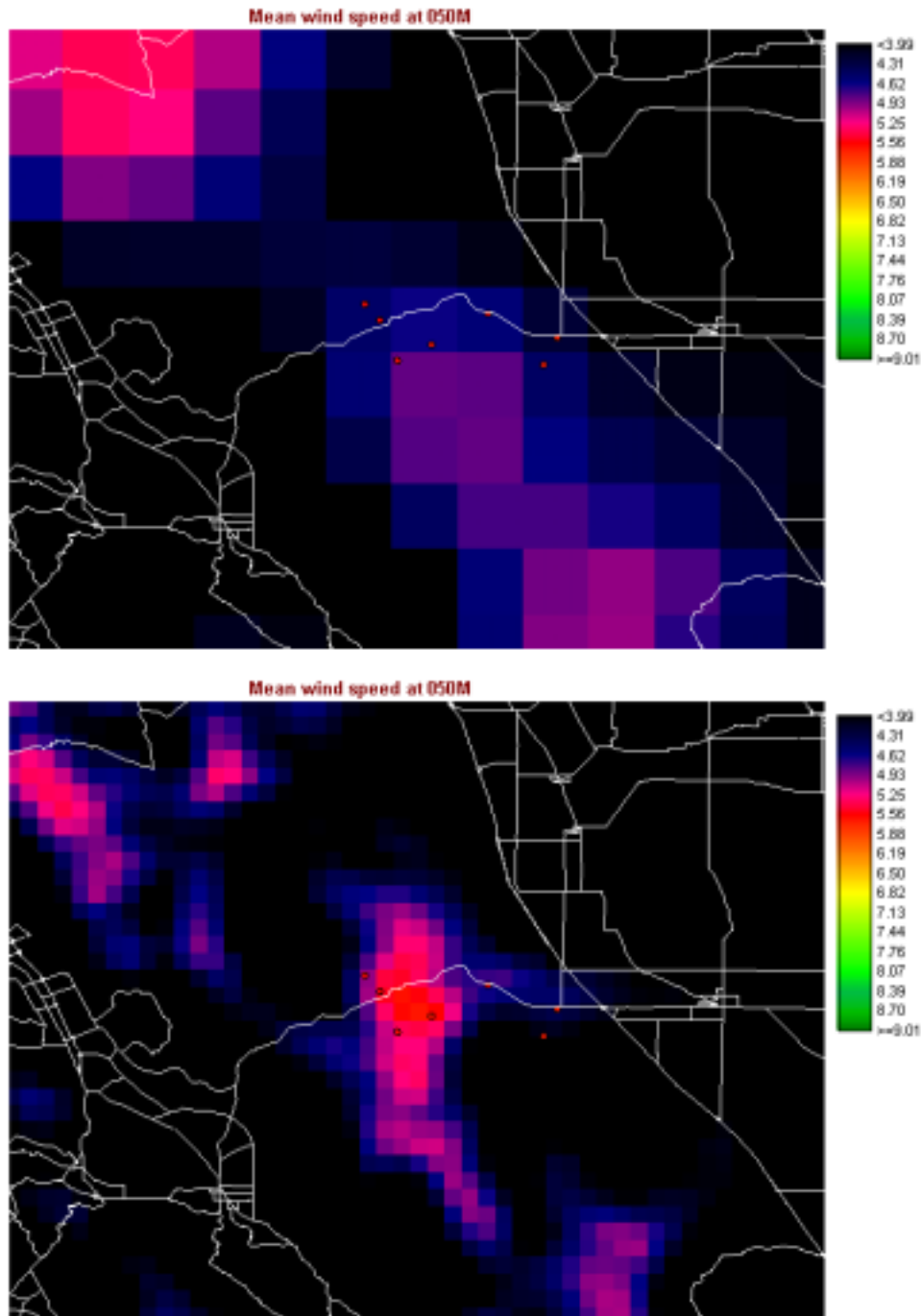


Figure 3.Effect of MASS grid scale on simulated winds through San Gorgonio Pass.



**Figure 4. Effect of MASS grid scale on simulated winds through Pacheco Pass.**

In the 8 km simulations (Figure 3, top), the pass is barely visible in the two green grid cells in the middle. At 2 km, the channeled winds are much stronger, reaching an average of nearly 9 m/s. Even so, the pass is spanned across its throat by only 4 to 5 grid cells, implying that the flow through the pass is not fully resolved and would become stronger at higher resolution. In Figure 4, the pass is almost entirely missed at the 8 km scale, but it appears more strongly at the 2 km scale (red area in the middle). However, the acceleration zone is only 3-4 grid cells wide – not enough to develop the full strength of the flow.

Grid scale is equally important in the ability of the MASS model to predict blocking by mountain ranges. California has unusually weak upper-air winds compared to the rest of North America. The most energetic flows actually occur within several hundred meters of the surface and can therefore be blocked rather easily by higher mountains. This is one of the main reasons why California's wind resource is concentrated in passes and corridors – there are few other paths for the low-level winds to reach the desert interior. At the 2 km scale of the MASS simulations, however, mountain ranges are smoothed out to some degree and may not, as a result, rise high enough to fully block the flow. Not only can this weaken the flow through the passes, it can result in an overestimation of the mountaintop winds. In high-resolution tests performed by TrueWind, mountaintop speeds in some locations dropped by 1 m/s or more compared to the 2 km simulations of this project.

The vertical, rather than horizontal, resolution appears to be a factor in the ability of the model to accurately simulate intense, low-level winds, such as those found in Solano County and the Montezuma Hills. The standard MASS configuration has 25 layers from the surface to the top of the atmosphere, with the first layer at 10 m and the second layer at approximately 30 m height above ground. We have tested the model with additional layers near the surface, and the result was that the simulated 50m wind speed in Solano County, the Montezuma Hills, and Altamont Pass increased by 4-6%.

An additional issue is the treatment of the thermally stable (nocturnal) boundary layer. In some valleys, as well as near the coast, it appears that the model may allow too much energy to be transferred through the nocturnal boundary layer to the surface. This may help explain why the model overestimated the extent of the wind resource south of Tehachapi Pass. A stable layer is frequently established at night in the desert valley downwind of the pass, preventing strong winds aloft from reaching the surface. Whether because of grid scale or some other reason, the MASS model appears to underestimate this effect.

The depth and persistence of the nocturnal boundary layer is equally important in understanding the rather high predicted wind resource in the valley to the east of the Sierra Nevada range near Little Lake and Haiwee. On the one hand, MASS may have overestimated the near-surface wind because of the difficulty of accurately simulating the deep stable boundary layer that is frequently established there. On the other hand, it is possible that the scant 10 m measurements and tree-flagging observations taken in this area have missed a very promising wind resource because the strong winds do not reach such a low height very often. We would not be surprised if measurements taken at turbine hub height revealed a much different picture than the sporadic winds observed at ground level. The effect of the nocturnal boundary layer on the wind energy resource in such situations is, consequently, a subject deserving much more research.

The effect of unreliable and undocumented data – beyond that accounted for in the estimated data error margin – must also be considered. The exact location and surroundings of many of the stations used in the validation were unknown. A simple problem such as the placement of a 10 m tower in the shadow of trees or buildings, or slightly below a mountain peak, could affect the observed wind speed by much more than the assumed error margin. Other sources of uncertainty include the anemometer type, calibration, and slope and offsets, as well as the degree of analysis and interpretation applied to the data.

We are particularly skeptical of data indicating a very low wind resource on several forested mountaintops, especially in northwestern California. In the absence of good site documentation, we suspect that several of these stations were heavily influenced by trees. Research using sodar – a technique for measuring wind profiles to heights of 100 m and more – shows that, on broad forested peaks, there can be an abrupt transition in the boundary layer from low winds near the surface to stronger winds aloft. Where such a transition occurs, both tree flagging observations and measurements taken from short towers may fail to detect the presence of a useful wind resource at a height accessible to wind turbines.

## 2.6. Adjustments to the Wind Maps

After reviewing the validation results and comments by the consultants, TrueWind proposed several adjustments to the wind map and submitted the adjusted map to NREL and the consultants for final review. This resulted in a few additional minor changes, which are incorporated in the maps presented here.

Figure 5 indicates where the adjustments were made. The adjusted speed is calculated by multiplying the initial (raw) speed or power by one plus the adjustment factor. The adjustment is assumed to be the same for all heights and seasons. In reality, the map error may vary with both season and height above ground, but since the data were not validated on a seasonal basis or at different heights, we assumed the adjustment would be the same.

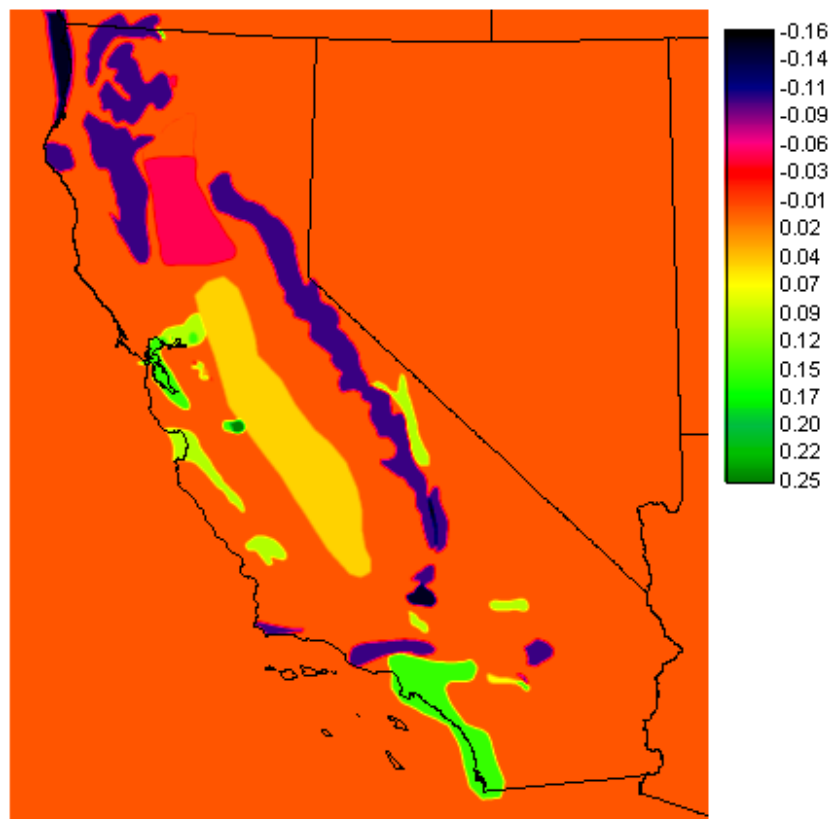
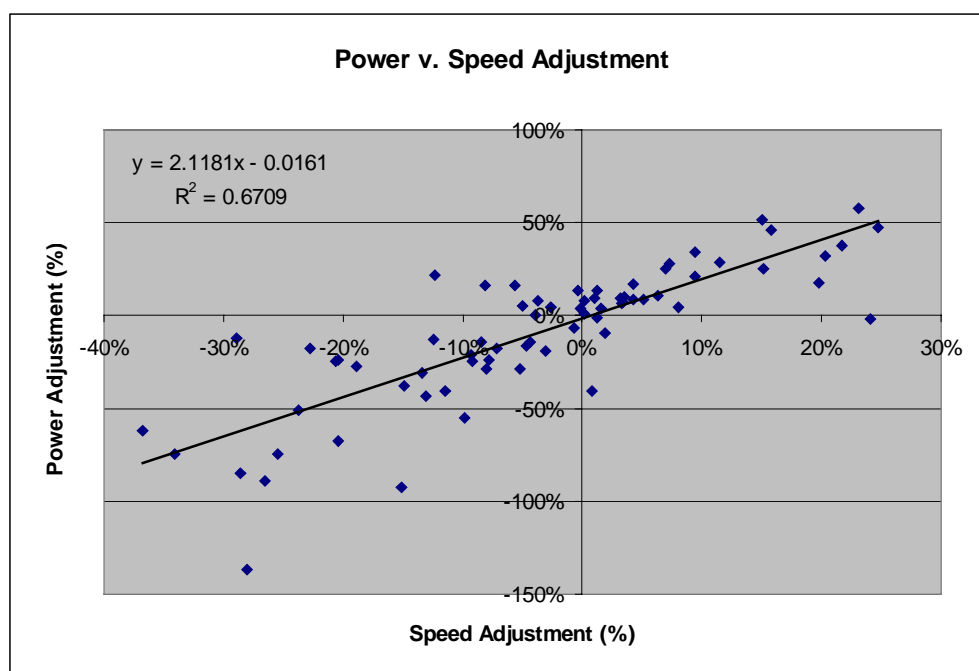


Figure 5. Wind speed adjustment factor.

The speed adjustment ranged from a decrease of up to 15% to an increase of up to 25%. Most adjustments were around 5-10% in either direction. Downward adjustments occurred along the coast of extreme northern California, in parts of the Tehachapi area where the outflow from the pass extended too far into the valley, in Owens Valley around Little Lake (because of an absence of data confirming the good resource there), and along mountaintops in northern California and coastal southern California. Upward adjustments were made within the San Joaquin valley and in certain coastal valleys, in Owens Valley near Bishop, in San Francisco Bay, and in several of the main wind resource areas.

Since we had much less wind power data than wind speed data, we decided not to attempt a separate wind power adjustment for each part of the state. Instead, we analyzed the relationship between the wind power and speed discrepancies for the 71 stations for which we had both types of data, and applied that relationship to convert the wind speed adjustment into a wind power adjustment.

Figure 6 plots the power adjustment that would be needed to eliminate the discrepancy between the map and data at each point, as a function of the corresponding speed adjustment. It is significant that the line passes very nearly through zero; this suggests that the predicted wind speed frequency distribution is, on average, neither too broad nor too narrow. At the same time, the slope of the line, 2.1, is much less than the expected value of 3.0 (based on the cubic relationship between power and speed).



**Figure 6. Adjustment in map power needed to eliminate the discrepancy with observations.**

Why are the wind power errors smaller than expected? We speculate that the nocturnal boundary layer may play a part. Where the predicted speed is too high, it may often be because the model underestimates the effect of a stable boundary layer in reducing the nighttime wind. If so, that would make the actual frequency distribution broader than the model predicts, and the wind power somewhat higher for the same mean speed; and that would, in turn, reduce the

apparent error in power compared to what would be expected from a strict cubic relationship. Conversely, where the model underestimates the mean speed, the cause may often be a low-level jet that makes the nighttime or morning wind comparatively strong; this would make the power appear somewhat low for the speed, and therefore also reduce the apparent power error. This idea is supported by the fact that the slope of the power v. speed adjustment for buoys is 2.5, whereas it is 2.0 for the inland stations; stability effects are much smaller offshore because ocean temperatures remain relatively constant throughout the day and night.

Based on this analysis, we set the wind power adjustment factor equal to 2.1 times the wind speed adjustment factor. An exception was made in the Montezuma Hills, where the ratio of power to speed adjustment was 3. (No separate wind power adjustment map is shown.

### **3.0 Outcomes**

A number of technical objectives were proposed for this project. The proposed objectives and their outcomes are as follows:

- Access state-of-the-art numerical modeling techniques to predict wind speed and power at various heights, and refine those predictions with validation data gathered from various meteorological towers throughout the state.

The MesoMap system was successfully used to predict the wind resource in the State of California on a 200 m grid. Maps and databases were generated for several heights above the effective ground level (forest canopy or ground). In addition, wind rose configuration at 50 m was predicted on a 2 km grid. Aside from confirming the existence of several well-known wind resource areas, the maps point to a number of other promising sites, some already known to wind energy experts, and others, perhaps, previously unsuspected.

The preliminary map estimates correlated well with data obtained for 266 towers and extrapolated to a height of 50 m, indicating that the method overall is sound. The map standard error in speed, without adjustments, was estimated to be between 5.7% and 8.4%, or 0.4-0.6 m/s, depending on the assumed uncertainty in the wind shear of the tower data. This level of error is comparable to the uncertainty in one year of data taken at 50 m height, with no climatological adjustment. Based on the validation, the preliminary maps were adjusted in places by amounts ranging from 5-25% (10-50% in power). The end result is believed to be more accurate than the validation statistics indicate; however this cannot be established independently without additional data.

- Create updated, high-resolution wind resource maps for California, including maps of wind speed and wind power at varying heights.

Maps 6-9 show the final mean wind speed at 30, 50, 70, and 100 m, and Map 10 the final mean wind power at 50 m. The map height is relative to the effective ground level. In dense forest, the effective ground level is the canopy height, which is typically about 2/3 the height of the treetops. For example, if the tree height is 15 m (45 ft), the effective ground level is about 10 m (30 ft), and a map height of 50 m therefore corresponds to a true height of 60 m above ground.

Easily the most noticeable aspect of the map is the high concentration of the wind resource in just a handful of areas. Those that are well known – Solano, Montezuma Hills, Altamont

Pass, Tehachapi Pass, and San Geronimo Pass – are easily seen. However the wind resource around Tehachapi Pass appears to be more extensive than is perhaps generally known (except by wind energy consultants). Good winds are found on the ridges on either side of the pass, on the slopes down into Antelope Valley, and possibly in sections of Owens Valley around Little Lake and Haiwee. The latter area, which has not been monitored, deserves further study. Another promising wind resource area lies at the border with Mexico: the mountain pass at Jacumba and its eastern slopes. The predicted wind power is especially high – NREL class 6 and 7.

Aside from these standouts, the wind resource is rather mixed in the rest of the state. The eastern California desert is predicted to have quite good winds in places, particularly on hills and mountains rising sharply from the desert floor; channeling around and between some of these terrain features may also result in localized areas of moderately good wind, for example, near Daggett. The low coastal mountains between San Luis Obispo and Santa Barbara offer another potential opportunity, with predicted wind speeds of 7-8.5 m/s in places along the ridgeline. Similar ridgelines can be seen elsewhere along the coastal range; and of course, some of the much higher mountains of the Sierra Nevada have good winds as well. However many of these areas will not be suitable for wind projects because they are in parks or national forests, or they are valued for scenic and other reasons.

- Create maps depicting the seasonal variability of the wind resource.

Maps 11 and 12 depict the seasonality of the wind speed and power. Different parts of the state have much different seasonal characteristics. In the state as a whole, summer tends to have the least wind, whereas frequent storms and passing weather fronts make the winter season windier, both on mountain peaks and in the southern desert. However, spring and summer favor stronger winds through the main wind corridors, especially Altamont and Pacheco passes, because of the intense heat generated in the desert.

- Create computer files of wind resource data that are ready for immediate integration into State cartography system (GIS format).

A CD-ROM containing GIS-compatible wind resource data files, both seasonal and annual, is provided separately. Instructions for the use of the data are provided on the CD-ROM and in Appendix II.

The land area in different wind speed and power bands is shown in Table 3. The total land area of the state is 158,339 sq. mi. at the map grid scale. The figures give a rough indication of the technical potential of wind energy in the state. For example, one might assume that an average of 15 MW of wind capacity could be installed on each square mile of suitable windy land. (The actual density depends on many factors, including the type of terrain, directionality of the wind, and size and efficiency of the turbine.) Then, assuming a hub height of 70 m, about 28,000 MW could theoretically be installed at sites where predicted mean wind speed is at least 7.5 m/s.

**Table 3. Land area in each wind speed or power band, in square miles.**

Height (m)		Mean Speed (m/s)					
	<4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	>8.5	
30	105161	38555	11136	2644	621	221	
		<5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5	>9.5
50		134716	17695	4583	1016	257	72
70		125374	24488	6593	1471	331	83
100		114033	32208	9524	2058	415	100
NREL Wind Power Class							
	1	2	3	4	5	6	7
50	120187	25130	7826	2749	1200	849	397

It should be emphasized that the mean wind speed or power at any particular location may differ substantially from the predicted values, especially where the elevation, exposure, or surface roughness differs from that assumed by the model, or where the model scale is inadequate to resolve significant terrain features. Furthermore, the map height should be interpreted as the height above the vegetation canopy. In dense forests with tall trees, the actual height above ground at which the predicted winds would be observed may be as much as 10-15 m higher than the nominal height.

Detailed guidelines for using the maps and adjusting the wind resource estimates where necessary are provided in Appendix II.

#### **4.0 Conclusions**

We have successively used the MesoMap system to predict the wind resources in the State of California at a high spatial resolution. Maps and databases have been produced for several heights above the effective ground level (forest canopy or ground). Aside from confirming the existence of several well-known wind resource areas, the maps point to a number of other promising sites, some already known to wind energy experts, and others perhaps previously unsuspected.

The preliminary map estimates correlated well with data obtained for 266 towers and extrapolated to a height of 50 m, indicating that the method overall is sound. The scatter plot of measured and predicted wind speed exhibited a strongly linear relationship, with little or no bias, and a  $r^2$  regression coefficient of nearly 80%. The map standard error in speed, without adjustments, was estimated to be between 5.7% and 8.4%, or 0.4-0.6 m/s, depending on the assumed uncertainty in the wind shear of the tower data. This level of error is comparable to the uncertainty in one year of data taken at 50 m height, with no climatological adjustment. Based on the validation, the preliminary maps were adjusted in places by amounts ranging

from 5-25% (10-50% in power). The end result, we believe, is more accurate than the validation statistics indicate; however this cannot be established independently without additional data.

#### **4.1. Recommendations**

While the maps produced in this project have been shown to be quite accurate, we have identified a number of shortcomings in the method and data used and recommend additional research and data collection to address these. Specifically,

1. High-resolution modeling of selected areas. Certain aspects of California's unusually complex wind regime, such as blocking by coastal mountains and channeling through narrow passes, could not be modeled very accurately at the 2 km grid scale of the MASS simulations. Higher resolution model runs could help refine the wind resource estimates in promising areas.
2. Analysis of boundary layer issues. The stability of the nighttime boundary layer can have a major impact on the wind resource in areas such as the California desert, by suppressing valley winds and enhancing winds on bluffs, for example; and yet it poses a significant modeling challenge. A focused program of research on improved methods for simulating the stable atmosphere could substantially improve the accuracy of the wind map in areas of promise of wind development.
3. Improved definition of land cover and surface roughness. Uncertainty in the height and density of trees, among other aspects of land cover, greatly increases the uncertainty in wind resource estimates on forested ridgelines and other locations. There are undoubtedly a great deal of data and human expertise on the types and characteristics of California's forests and land cover types which were not brought to bear in this project. A study to synthesize such information and apply it to wind energy assessment is recommended.
4. Measuring the wind aloft. Most of the towers that provided data for the validation of the maps were less than 10 m in height. Lack of knowledge of the wind shear consequently introduced a large uncertainty in the wind resource at the hub height of wind turbines. New measurements using taller towers in promising yet unexplored areas are certainly needed. However, even the current generation of 50 m towers do not reach the hub height of modern turbines, which is typically 70 or 80 m, let alone the tops of their blades, which may reach 130 m. Sodar, a tool for measuring the vertical wind profile to heights of 200 m or more, can provide valuable additional information at a moderate cost. In addition to exploring the wind resource at a particular site, sodar could be very useful in validating and refining models to simulate the boundary layer, with benefits in other areas being mapped.

#### **4.2. Benefits to California**

The purpose of the maps is to enable planners, energy providers, developers and other users to make informed decisions regarding policy and investment decisions relevant to wind energy generation.

From the developer perspective, the maps will identify sites suitable for detailed wind resource assessment and increase the chances that such studies will reveal economically developable resources.

Governmental planners may use the data to help identify economic development opportunities and the needed permitting/policy changes required to assist development.

The reduction in costs that result from lowering the risk of site assessment and streamlining the permitting process supports the overall goal of improving the energy cost/value of California's electricity.

It is hoped that new indications of known and formerly unknown promising wind resource sites may lead to new wind resource projects which will help meet California's future electricity needs.

## **Appendix I: Guidelines for Use of Maps**

## **Appendix II: The Data CD-ROM**

## Appendix III: Maps

### List of Maps

Map 1. MesoMap grid setup

Map 2. Elevations

Map 3. Land covers

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Map 5. Validation sites

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Map 7. Predicted mean wind speed at 50 m

Map 8. Predicted mean wind speed at 70 m

Map 9. Predicted mean wind speed at 100 m

Map 10. Predicted mean wind power at 50 m

Map 11. Predicted seasonal variation of the mean wind speed at 50 m

Map 12. Predicted seasonal variation of the mean wind power at 50 m